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THE TIMESCALES OF THE OPTICAL VARIABILITY OF BLAZARS. II. AP LIBRAE

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ABSTRACT

The BL Lacertae object, AP Librae, has been photometrically monitored in an effort to study the nature of optical variations which may occur on timescales less than a day. Rapid, large amplitude events have been observed with changes as large as 1.0 mag from night to night. The most rapid rate of change detected was 0.06 ± 0.01 mag/hr. This is one of the most rapid, large amplitude events ever detected for a BL Lacertae object.

1. INTRODUCTION

An ongoing program to investigate the question of the existence of variations in the total optical flux for BL Lacertate objects on timescales significantly less than a day utilizing modern CCD detectors has been undertaken. Preliminary results reported for BL Lac (Miller *et al.* 1989) and OQ 530 (Carini *et al.* 1990, hereafter referred to as Paper I) have demonstrated the reality of microvariability for these two objects. In the present paper, we report the results of a similar study of the variability of AP Librae.

The variable object, AP Librae, was initially identified as the optical counterpart of the radio source PKS 1514 − 24 by Bond (1971) and Biraud (1971). This object had previously been identified with a faint, compact galaxy by Bolton *et al.* (1965) and Westerlund & Wall (1969). Several decompositions of the galaxy and the variable nonthermal central source have been attempted (Disney *et al.* 1974; Kinman 1976; Visvanathan & Griersmith 1977; McGimsey & Miller 1978; Baxter *et al.* 1987; Westerlund *et al.* 1982). Strittmatter *et al.* (1972) and Bond (1973) first suggested that AP Librae was a member of the BL Lacertae class of objects. The optical variability of this object was first observed by Ashbrook (1942). More recently, Miller *et al.* (1974), Westerlund *et al.* (1982) and Webb *et al.* (1988) have studied the optical variability of this object. Webb *et al.* (1988) have detected a total range of ~3.0 mag for AP Librae. Photographic studies of the optical variability of AP Librae by Miller *et al.* (1974) suggested variations of 0.5 mag on timescales of less than one day. The results of the present investigtion conclusively demonstrate, for the first time, the presence of rapid variations for AP Librae similar to those suggested by the earlier observations of this object by Miller *et al.* (1974).

2. OBSERVATIONS AND DATA REDUCTIONS

The observations of AP Librae reported here were obtained with the No. 1 0.9 meter telescope at Kitt Peak National Observatory equipped with a direct CCD camera and an autoguider and with the 24 in. telescope at Lowell Observatory equipped with a similar CCD camera. The observations were made through a V filter with an RCA CCD. Repeated exposures of 180–240 s were obtained for the star field containing AP Librae and several standard stars. These standard stars, located on the same CCD frame as AP Librae, provided comparisons for use in the data reduction process. The observations were reduced using the method of Howell & Jacoby (1986). Each exposure is processed through an aperture photometry routine which reduces the data as if it were produced by a multistar photometer. Differential magnitudes can then be computed for any pair of stars on the frame. Thus, simultaneous observations of AP Librae, several comparison stars and the sky background will allow one to remove variations which may be due to fluctuations in either atmospheric transparency or extinction. The aperture photometry routine used for these observations is the APPHOT routine in IRAF.[3]

An analysis of the error in a given CCD observation must consider many possible sources of error associated with that particular observation. The sky background, the read noise of the CCD chip, and the dark count are all possible sources of error which must be considered. If their contributions are found to be negligible, then simple photon statistics, i.e., $1/\sqrt{N_*}$, where N_* is the total number of sky subtracted counts in the object, adequately describes the error in the observations. If the contributions of the aforementioned sources of error are not negligible, then simple photon statistics underestimate the error associated with an observation. In this case, the errors can be calculated via the CCD equation (Howell 1989),

$$S/N = \frac{N_*}{\sqrt{N_* + n_{\rm pix}(N_{\rm sky} + N_{\rm d} + N_{\rm r}^2)}}, \qquad (1)$$

where N_* = the number of sky subtracted counts in the object, $n_{\rm pix}$ = the number of pixels in the measuring aperature, $N_{\rm sky}$ = the number of counts in the sky, $N_{\rm d}$ = the dark count of the CCD chip, and $N_{\rm r}$ = the read-out noise of the CCD chip. Howell (1989) has shown that for the RCA CCD chips used in this investigation, simple Poisson statistics will not adequately describe the errors for the objects with $V \geqslant 18.0$. The primary reason for this is that the RCA CCDs used in this investigation have high read-out noise, which enters into the CCD equation squared, and thus can contribute significantly to the noise.

In the process of differential photometry, one observes a

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[1] Guest Observer, Kitt Peak National Observatory which is operated by the Association of Universities for Research in Astronomy, Inc.

[2] Guest Observer, Lowell Observatory.

[3] IRAF is distributed by the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc. under contract to the National Science Foundation.

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variable object V, a comparison star C, and a check star K. Ideally, one would like to have V, C, and K nearly equal in brightness. In this case, the σ of the $C-K$ light curve would describe the errors in the $V-C$ light curve, since all three objects are nearly equal in brightness. An alternative to this situation, which has been shown to be acceptable (Howell *et al.* 1988) is to have V equal to C or K and have the remaining comparison somewhat brighter than V. Unfortunately, neither of these situations is easily obtainable in practice. Usually V, C, and K are at different magnitudes and one must find a way to scale the σ in the $C-K$ data to the σ in the $V-C$ data. Howell *et al.* (1988) describes a method by which one can calculate a scale factor Γ^2 which allows one to scale the σ^2_{C-K} to the σ^2_{V-C} via knowledge of the characteristics of the CCD, the counts in V, C, K, and the sky, and the size of the measuring aperture. One assumes that C and K have no intrinsic variability and that the process of differential photometry eliminates the common sources of error between the objects on a CCD frame, i.e., a common sky background and extinction effects. This allows one to assume that the CCD noise variations and photon statistics are independent in the three objects. In addition, Howell *et al.* (1988) report that even random errors not explicitly considered in the CCD equation are scaled from $C-K$ into $V-C$. This method has been applied to observations of cataclysmic variable stars obtained with 1 m class telescopes and with accuracies as good as 0.05 mag for objects at $V=19.0$ (Howell *et al.* 1988, Howell & Szkody 1988).

Following Howell *et al.* (1988), the variance in the $V-C$ data can be thought of as containing two components. One of these, $\sigma^2_{V-C}(\mathrm{INS})$ is the variance in $V-C$ resulting from the noise sources in the data and the other, $\sigma^2_{V-C}(\mathrm{VAR})$ is the variance resulting from the intrinsic variability in $V-C$. Thus

$$\sigma^2_{V-C}=\sigma^2_{V-C}(\mathrm{INS})+\sigma^2_{V-C}(\mathrm{VAR}). \tag{2}$$

If V were not variable, then the second term on the right-hand side of the equation would equal zero, and the variance in $V-C$ would lead to a description of the errors in the $V-C$ data. This also says that if one could somehow remove the variations in $V-C$ that were intrinsic to the variable, then the variance would again lead to a description of the error in $V-C$.

The errors for $V-C$ have been calculated assuming that the variations intrinsic to V can be identified and removed. If the observed variations covering several hours can be characterized as a linear trend, then these trends can be fit with a straight line via a least squares analysis. The deviation of each point from this line is calculated, summed and normalized to the number of data points and the square root of this normalized sum is then taken and used as the error for the $V-C$ data. This method has also been used on the standard stars and the results compared to the standard deviations calculated in the usual fashion. No significant difference was found between the σs calculated by either method.

One should also consider another contribution to the estimate of the errors determined in the manner described above. What if low amplitude, erratic variations exist in the blazar? These variations are then included as a noise source when, in fact, they are intrinsic to the blazar. Such variations, if they are present, are certainly important. However, the variations under consideration are those which constitute, in most cases, well-defined linear trends or outbursts and from which one can derive variability timescales and estimates of physical parameters of the sources. Any erratic, low amplitude variations do not fit these criteria, and need much better signal-to-noise data and larger telescopes to be properly investigated. Thus, they have not been considered in this investigation, but will be the subject of future studies. The presence of such variations will increase the estimate of the errors in the $V-C$ data. Therefore the adopted error provides one with a much more conservative estimate of the errors.

Another possible source of error and/or spurious variations could be due to the presence of the underlying galaxy component in AP Librae. AP Librae showed only a faint nebulosity around the stellar nucleus on the CCD frames obtained for this investigation. As a test of the possible effects of a galaxy component contributing to the variability detected in the aperture photometry, consider Fig. 1, which is the light curve of the Seyfert galaxy MCG 8-11-11 obtained on the night of 17 March 1989. The top panel displays the object minus a comparison star, the bottom panel displays the difference between the comparison star in the top panel and another comparison star in the field of MCG 8-11-11. MCG 8-11-11 has a very prominent galaxy component associated with it, one that is much more conspicuous than that of AP Librae. Yet, there is no evidence that this has contributed to the errors in the data, or introduced any spurious variability. The object and comparison stars were both reduced with the same size aperture, and the aperture was the same over the length of the observations. The standard deviation of the differential magnitudes between MCG 8-11-11 and the comparison is 0.006, while the differential magni-

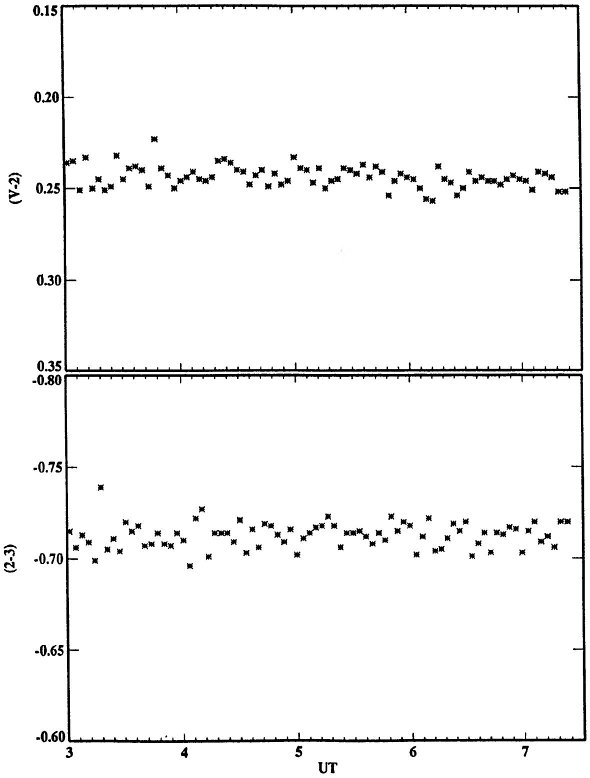

FIG. 1. The light curve of the Seyfert galaxy MCG 8-11-11 from 17 March 1989.

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tudes of the comparison stars exhibit a standard deviation of 0.007.

Variations in either the seeing or transparency of the Earth's atmosphere could change the amount of galaxy component present in the aperture and introduce spurious variations. To test this, consider again the observations of the object MCG 8-11-11 from the night of 17 March 1989. Figures 2–4 display plots of the instrumental light curves of the object and the two comparison stars used in the reductions. If the night is truly photometric and no intrinsic variations are occurring in an object, one would expect a gentle slope in the data due to extinction, and nothing else. Any other variations are the result of either variations in the Earth's atmosphere or in the CCD itself. We see these other variations in all three plots shown. Note that these objects were found on different parts of the CCD chip and it is hard to envision an intrumental effect which would occur across the entire chip and that would behave in the fashion illustrated by the light curves. This data was obtained with an automatic guiding system, so one can also rule out the possibility that the variations are the result of the stars being placed on different portions of the CCD at different times during the course of the night's observation. Thus, we are left with the assumption that these variations represent changes in the conditions of the atmosphere. If one considers Fig. 2, we see that these variations are absent in the differential light curve displayed in the bottom panel, thus these effects are removed in the process of differential photometry, even for an object with a galaxy component as strong as MCG 8-11-11. Therefore, any spurious variations that are the result of seeing and/or transparency changes are small compared to the other sources of error considered and certainly could not be responsible for the linear trends observed for AP Librae.

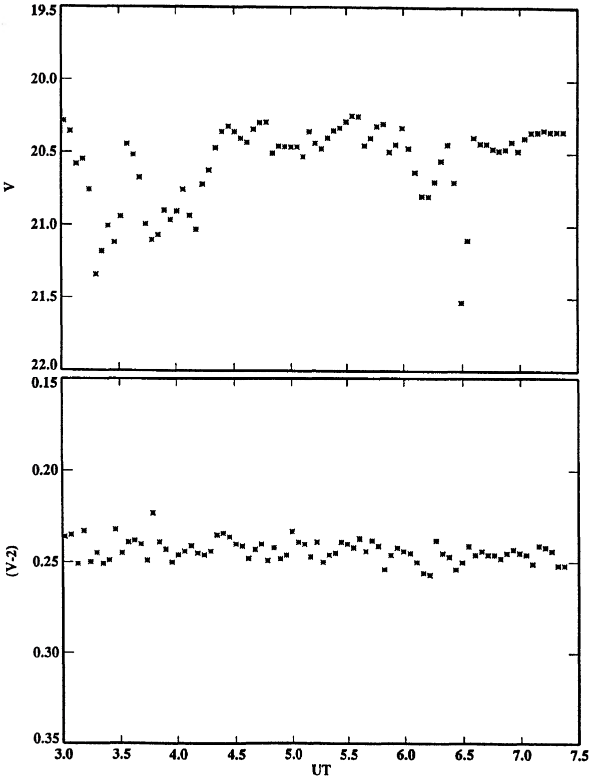

FIG. 2. The instrumental light curve for MCG 8-11-11 is displayed in the top panel, and the differential light curve is displayed in the bottom panel.

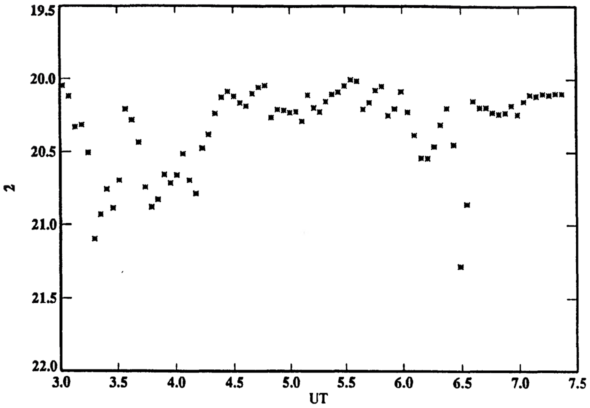

FIG. 3. The instrumental light curve for comparison star 2 in the field of MCG 8-11-11.

3. RESULTS

In Table 1, a summary of the observations of AP Librae is presented. Column 1 lists the date of the observations, column 2 the observatory/telescope used, column 3 the uncertainties in the observations, column 4 the amplitude of the detected variability, and column 5 the duration of the night's observations, in hours. The results of the observations of AP Librae obtained March–May 1989 are displayed in Figs. 5–9. The upper panel in each figure displays the differential magnitude between a comparison star and AP Librae. The lower panel displays the differential magnitude between two comparison stars in the field of AP Librae.

AP Librae was intensively studied in March 1989 to establish the existence of microvariability. In a 14 day period from 5 to 18 March 1989, the source was observed seven nights. Unfortunately, no photoelectric comparison sequence exists for this object, so *V* magnitudes cannot be quoted for these observations. In addition, different standards were chosen from observing run to observing run (and sometimes night to night) which does not allow any comments to be made

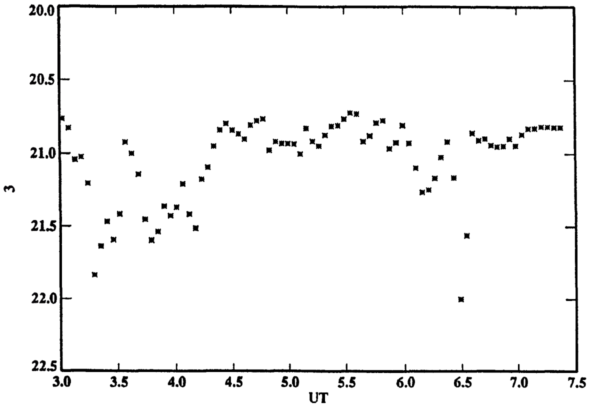

FIG. 4. The instrumental light curve for comparison star 3 in the field of MCG 8-11-11.

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TABLE 1. Summary of the observations of Ap Librae.

Date	Observatory	Error	*A*	*D*
3/5/89	Lowell(42)	0.037	—	2.3
3/6/89	Lowell(42)	0.010	—	2.5
3/7/89	Lowell(42)	0.006	—	2.8
3/14/89	KPNO(36)	0.044	—	3.0
3/16/89	KPNO(36)	0.026	0.20	3.0
3/17/89	KPNO(36)	0.010	—	3.0
3/18/89	KPNO(36)	0.019	0.10	3.0
5/18/89	Lowell(24)	0.019	0.10	4.3
5/19/89	Lowell(24)	0.015	—	2.1

concerning the overall variability of the object during this time period. Different standards were chosen because stars of comparable brightness to the object which might be used as standards lie too far away from the object to be centrally placed on the CCD frame with the object. So, in different observing runs, the object was placed on different parts of the chip to determine where suitable standards near the object might lie.

Figure 5 displays the results of the observations made from 5–7 March 1989. From 5 to 6 March, the source exhibited an ~0.05 mag decline in its brightness. This decline continued from 6 to 7 March, with the source fading an additional ~0.15 mag. No significant variations were observed on any of the individual nights the source was observed. Figure 6 displays the results of the observations obtained 14–18 March 1989. From 14 to 16 March, the source declined in brightness by ~1.2 mag and then from 16 to 17 March, the source recovered by ~0.60 mag. This recovery continued from 17 to 18 March, with the surce brightening by an additional ~0.25 mag. The source exhibited no significant variations on the night of 14 March 1989. The variations which appear to be present on this night are not at a statistically significant level since the scatter of the data points about the linear trend in the $V-C$ curve is substantialy larger on this night than was observed on the other nights. The following night, 16 March 1989, the source shows an increase in brightness of ~0.20 mag over the length of the observations (Fig. 7). The next night, 17 March 1989, the source showed no significant variations. Figure 8 displays the results of the observations obtained on 18 March 1989. The source was observed to decrease in brightness by ~0.08 mag over the course of the observations obtained on this night.

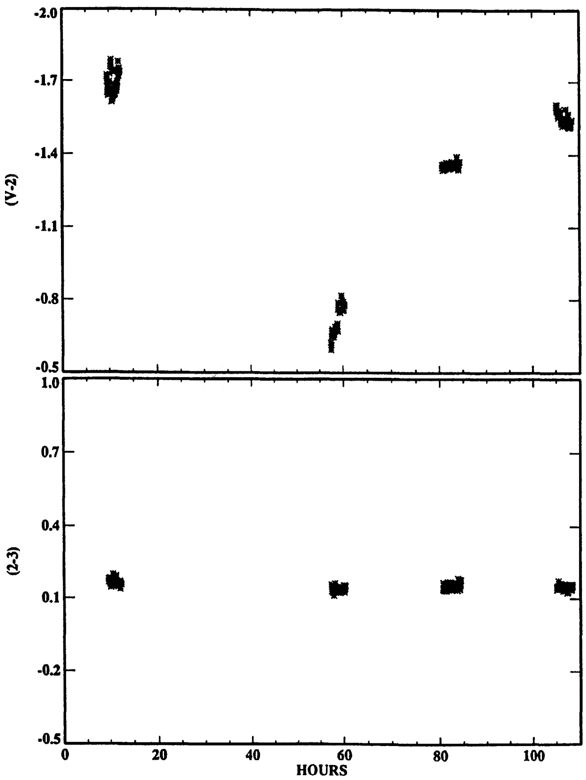

FIG. 6. The V observations of AP Librae obtained from 14–18 March 1989. The comparison stars are field stars of unknown brightness. 0 hr corresponds to 0 hr UT on 14 March.

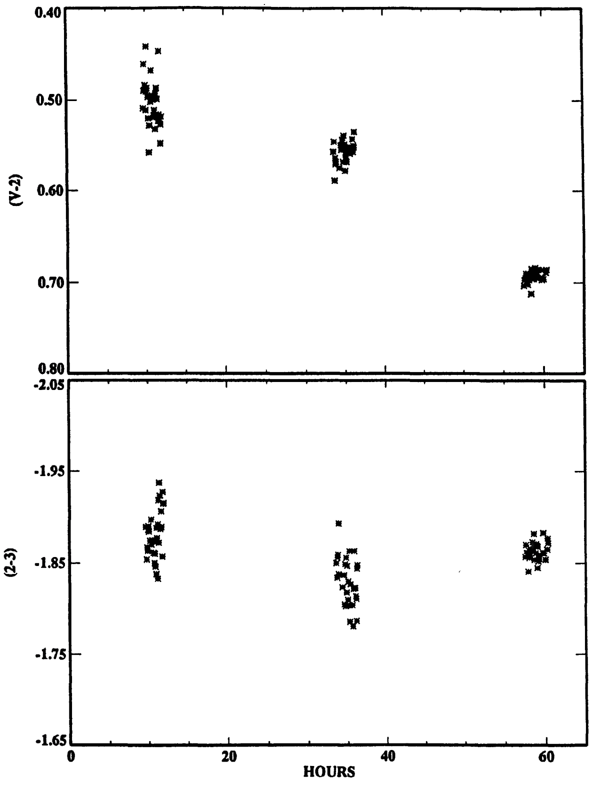

FIG. 5. The V observations of AP Librae obtained from 5–7 March 1989. The comparison stars are field stars of unknown brightness. 0 hr corresponds to 0 hr UT on 5 March.

AP Lib was also observed for three nights from 18–21 May 1989. From 18 May to 19 May 1989, the source increased in brightness by ~0.05 mag, followed on 19 to 21 May by a similar decrease of ~0.05 mag. On the night of 18 May, the source exhibited a ~0.08 mag decline in brightness over the 4 hr it was observed (Fig. 9). No significant variations were detected on the night of 19 May 1989 and only one data point was taken on the night of 21 May 1989.

The variations observed in Figs. 7–9 are very similar to the variations reported by Miller, *et al.* (1974) for AP Librae. In particular, both the long term light curves and rapid short term events such as those observed 1973 April 9 and 1973 May 4 by Miller *et al.* are consistent with the variations observed 1989 March 16 and March 18. The large-amplitude

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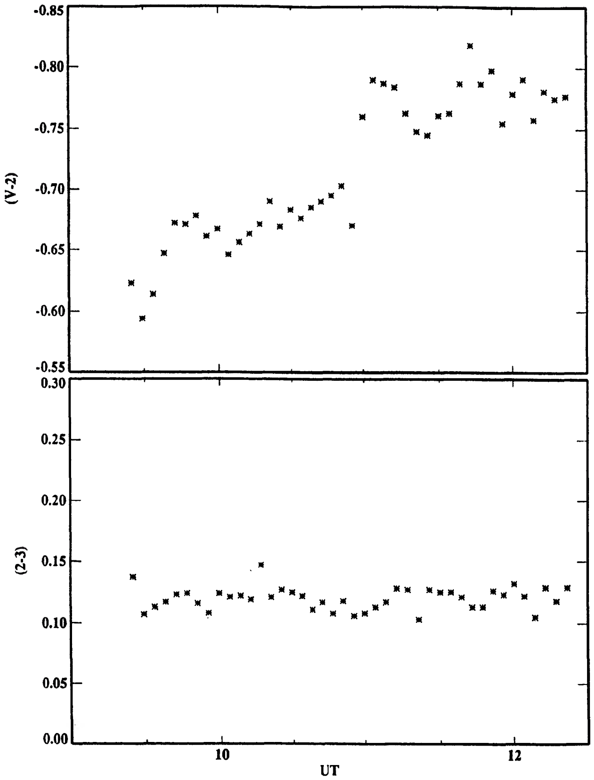

FIG. 7. The V observations of AP Librae obtained 16 March 1989 are displayed in the top panel. The comparison stars are field stars of unknown brightness.

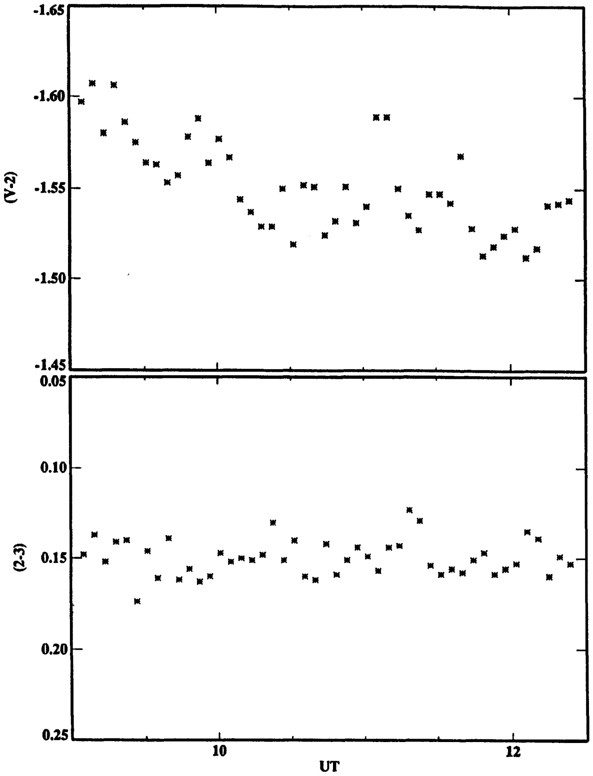

FIG. 8. The V observations of AP Librae obtained 18 March 1989 are displayed in the top panel. The comparison stars are field stars of unknown brightness.

event observed March 16 is one of the most rapid, large-amplitude events ever detected for any blazar.

Assuming such events arise from global, rather than local changes in the source, one may use such events to calculate a characteristic timescale, or doubling time which, in turn, can be used to estimate the size of the emitting region from $R \leqslant ct$, assuming that no relativistic bulk motion of material is present. If one further assumes that the radiation is generated in the vicinity of a black hole, e.g., $R \sim 3R_s$ where $R_s = 2G\mathcal{M}/c^2$ is the Schwarzschild radius, then an upper limit to the mass of the supermassive black hole is given by

$$\mathcal{M} \leqslant (c^3 t/6G). \tag{3}$$

The doubling time was calculated by identifying the most rapid significant variation, and calculating the resulting fastest observed rate of change. This fastest rate of change was calculated as follows. The endpoints of the variation were determined by eye, then the segment of the data in between these endpoints was fit via a least squares technique. In order to calculate the doubling time, the segment of data representing the fastest rate of change was converted from magnitude to flux units, then fit via a least squares technique to find the rate of change in flux units dF/dt. The timescale for a variation of ΔF is given by $\Delta F/(dF/dt)$. For a doubling of flux, $\Delta F = 2F_{\rm min} - F_{\rm min} = F_{\rm min}$, where $F_{\rm min}$ is the minimum flux observed over the course of the variation. So, the doubling time is found from $\Delta t = F_{\rm min}/(dF/dt)$. The uncertainties quoted for the mass estimates include both the uncertainty in the flux measurement and the errors in the least squares fit. The uncertainty in the source luminosity L_{λ_e} was calculated using the range of variations the object showed on that given night, rather than the internal measurement errors. The resulting mass limit calculated from this analysis is referred to as the variability mass, to uniquely identify it with a mass limit calculated from these variability arguments. This method of calculating the doubling time and resulting mass limit has been refined since Paper I. A reanalysis of the data in Paper I based on the discussion above leads to a refined variability mass limit for OQ 530 of $\mathcal{M}_{\rm var} \leqslant 2.0 \pm 0.7 \times 10^9 \mathcal{M}_\odot$. This change in the variability mass limit does not affect any other conclusions based on the observations presented in Paper I.

The most rapid rate of change observed in AP Librae was 0.06 ± 0.01 mag/hr, observed on the night of 16 March 1989, from UT 9.42 to 12.37. A doubling time calculated from this variation leads to an upper limit on the variability mass of $\mathcal{M}_{\rm var} \leqslant 2.0 \pm 0.2 \times 10^9 \mathcal{M}_\odot$. The Eddington luminosity for a blackhole of mass $\mathcal{M}$ is given by Wiita (1985),

$$L_{\rm E} = 1.3 \times 10^{38} (\mathcal{M}/\mathcal{M}_\odot) \text{ergs/s}, \tag{4}$$

which yields $L_{\rm E} \leqslant 2.6 \pm 0.3 \times 10^{47}$ ergs/s. Since none of the observed comparison stars were calibrated, an estimate of the source luminosity can only be made based on this object's average brightness and historical range of variability. This gives a magnitude for AP Lib of $\sim 15.0 \pm 1.5$, which yields an observed luminosity of $L_{\lambda_e} \sim 7.6 \pm 0.7 \times 10^{41}$ ergs/s. Applying a bolometric correction of 9.0×10^4 (Carini 1990) gives $L_{\rm bol} \sim 6.8 \pm 0.6 \times 10^{46}$ ergs/s. Thus, while we find mi-

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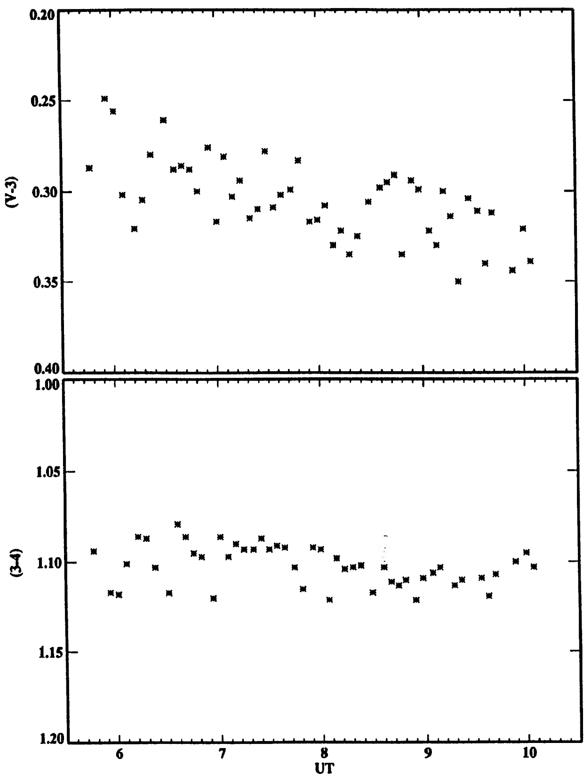

FIG. 9. The *V* observations of AP Librae obtained 18 May 1989 are displayed in the top panel. The comparison stars are field stars of unknown brightness.

crovariability is definitely present on extremely short timescales, which in turn suggests a very small source region, the luminosity of AP Librae is less than the Eddington luminosity and most likely does not require relativistic beaming for its explanation.

The question of whether or not the small, several percent, variations observed in these objects are the result of global or local changes in the source region still remains unanswered. Thus, the appropriateness of extrapolating such variations to calculate a doubling time and hence source parameters is also unclear. However, if one observes an event which approaches an observed doubling in the source luminosity, one can be reasonably confident that such an event represents a global, rather than local, change in the source. Such changes have been observed in this investigation (see Fig. 6). If one takes the most rapid of these events, which is a factor of ~1.8 change in ~24 hr observed from 1989 March 16 to March 17 and extrapolates it to a doubling time, we find the limit to the variability mass of AP Lib to be $\mathscr{M}_{\rm var} \leqslant 3.3 \pm 0.4 \times 10^9 \mathscr{M}_\odot$. Thus, the mass limit calculated from the larger observed variations is consistent with that calculated from the extrapolation of the small observed variation. The 0.06 mag/hr change used to calculate the mass limit in the preceeding paragraph is part of the large change used to calculate the mass limit presented above, so this result is not too surprising. However, it does suggest that the assumption that these smaller variations are representative of changes in the source as a whole is adequate, provided that these small changes are part of larger, longer term changes in the source.

In summary, the optical variations reported here are among the most rapid, large amplitude events detected for any BL Lacertae object. These events may be used to place constraints on the size of the source region, if they are the result of global changes in the source. However, the luminosities observed are sub-Eddington, and therefore one does not necessarily need to resort to relativistic beaming in order to explain these variations.

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